Answer to the reviewer 1

The paper went through a deep revision in which we: i) revised the language, ii) modified the paper structure (separating the discussion section from the result section, highlighting the main finding in the conclusion section), iii) improved the abstract, introduction, and methodology sections, iv) we changed and improved the figures' quality and captions.

Finally, we extended the level of discussion and we added more citation to justify and compare with our findings.

Moreover, we added the new analysis requested by the reviewer n1 and n. 2, specifically:

a) As both the reviewer asked, we used the methodology of linear interpolation in time instead of the closest-year method presented in the original version of the paper
b) to disentangle the effect of each single components of the risk on its total changes, changing in turn one by one each element (i.e. vulnerability, exposure and hazard) and keeping constant the other two
c) finally we also improved our trend analysis and statistical significancy evaluation by using the FDR methodology.

Answers to the Reviewer 1

We thank the reviewer for the revision and the useful comments and insights. We reviewed the paper according to the suggestions and below you can find a one-to-one answer. The answer to the reviewer comments are provided in red, the new revised sentences are provided in blue.

General comments

The paper presents a 38-year quantification of the risks from heatwaves (HW) and coldwaves (CW) in the region of Trentino-Alto Adige in Italy. In precise, the authors try to quantify hazard, exposure, and vulnerability from HW and CW using the Heat Wave Magnitude Index daily/Cold Wave Magnitude Index daily, the Tweedie zero-inflated distribution, high-resolution maps of the population, and a set of eight socioeconomic indicators. They claimed that this new method for the calculation of human risk from HW and CW is applicable to other regions. The manuscript has an important aspect as it offers an additional contribution to understanding the spatio-temporal risk of HW / CW. Although, I have several comments on the methodology and the presented results. In general, the level of discussion is almost minimal, while most of the statements are too often very general, missing any proper citation and profound discussion that would put their results in a comparative context. My impression is that the paper is incomplete and can be improved. I, therefore, recommend that the paper goes a major revision, and the authors need to respond to the issues I list below before the paper can be accepted for publication in NHESS

We thank the Reviewer for the valuable and constructive feedbacks, which have been very much appreciated. The paper has undergone the suggested major revision in which all the suggestions have been included. Please see below the one-to-one answers to the reviewer comments.

Main comments

1. The abstract is very extended. It must be much shorter including only the key points of the manuscript.

Thank you for your feedback on this, it has been shortened and the key points are better highlighted.

The old abstract is:

Heat waves (HW) and cold waves (CW) can have considerable impact on people. Mapping risks of extreme temperature at local scale accounting for the interactions between hazard, exposure and vulnerability remains a challenging task. In this study, we quantify human risks from HW and CW at high resolution for theTrentino-Alto Adige region of Italy from 1980 to 2018. We use the Heat Wave Magnitude Index daily (HWMId) and a Cold Wave Magnitude Index daily (CWMId) as temperature-based indicators and apply a Tweedie zero-inflated distribution to derive hazard intensities and frequencies. The hazard maps are combined with high-resolution maps of population, for which the vulnerability is quantified at community and city level using a set of eight socioeconomic indicators. We find a statistically significant increase in HW hazard and exposure, with 6.0-times more people exposed to extreme heat after 2000 compared to the last two decades of the previous century. CW hazard and exposure remained stagnant over the studied period in the region. We observe a general trend towards increased resilience to extreme temperature spells over the region. In the larger cities of the region, however, we find that vulnerability has increased due to an ageing population and more single households. HW risk has risen practically everywhere in the region, indicating that the reduction in vulnerability in the smaller communities is outpaced by the increase in HW hazard. In the large cities, HW risk levels in the 2010s are 50% larger compared to the 1980s due to the rise in both hazard and vulnerability. Whereas in smaller communities, stagnant CW hazard and declining vulnerability results in reduced CW risk levels, the risk level in cities grew by 20% due to the increased vulnerability over the study period. The findings of our study are highly relevant for steering investments in local risk mitigation measures, while the method can be applied to other regions that have detailed information on hazard, exposure and vulnerability indicators.

The revised version abstract is below:

Heat waves (HWs) and cold waves (CWs) can have considerable impact on people. Mapping risks of extreme temperature at local scale accounting for the interactions between hazard, exposure and vulnerability remains a challenging task. In this study, we quantify risks from HWs and CWs for the Trentino-Alto Adige region of Italy from 1980 to 2018 at high spatial resolution. We use the Heat Wave Magnitude Index daily (HWMId) and the Cold Wave Magnitude Index daily (CWMId) as the hazard indicator. To obtain HWs and CWs risk maps we combined: i) occurrence probability maps of the hazard, ii) normalized population density maps, and iii) normalized vulnerability maps based on eight socioeconomic indicators. The occurrence probability of the hazard is obtained using the Tweedie zero-inflated distribution. The methodology allowed us to disentangle the effects of each component of the risk to its total change.

We find a statistically significant increase in HWs hazard and exposure while CWs hazard remained stagnant in the analyzed area over the study period. A decrease in vulnerability to extreme temperature spells is observed trough the region except in the larger cities where vulnerability has increased. HWs risk increased in 40% of the region, with it being stronger in highly populated areas. Stagnant CWs hazard and declining vulnerability result in reduced CWs risk levels, with exception of the main cities where it grew due to their increased vulnerabilities and exposures.

The findings of our study are relevant to steer investments in local risk mitigation, and this method can potentially be applied to other regions that have similar detailed data.

2. I would propose a reconstruction of the introduction. It does not have coherence, especially when going from one paragraph to another, and it is extended compared to the other sections. The novelty of the study is not being appropriately highlighted. Concerning novelty, the authors could also emphasize the advantages of applying specifically the form of Tweedie for the zero-inflated distribution. The limitations of this method should be accounted and properly included in the manuscript.

Thank you for your suggestion on this, your constructive feedback has been taken into account, the introduction has been shortened and has been rearranged with a better emphasis on the point mentioned. The Introduction of the revised paper is structured as follows:

1) importance of HWs and CWs from a global to the local scale
2) definition of the HWs and CWs risk as product of hazard, exposure, and vulnerability
3) how the single risk components have been computed in different studies and what are the main challenges in defining them as well introducing Tweedie as a possible solution to one of these challenges, i.e., accounting for zero inflation.
4) The need to move to a high-resolution risk analysis and goals and objectives of our study

The advantages and limitations of using a tweedie methodology has been highlighted as well and is present both in the introduction as well as in the new limitation section of this study. This has been done with the following new sentences:

The main advantage of the Tweedie distribution is the possibility of considering many distributions for the continuous and semi-continuous domain such as: normal, Gamma, Poisson, Compound Gamma-Poisson, and Inverse Gaussian (Bonat and Kokonendji, 2017; Rahma and Kokonendji, 2021; Shono, 2008; Temple, 2018). Moreover, for some of these distributions (i.e. Poisson mixtures of gamma distributions) it explicitly enables the fitting of zero-inflated data. Tweedie distribution main limitation is the complex distribution's fitting methodology and the difficulties to compare it to other models via information criteria such as the Akaike's information criterion (Shono, 2008)

3. Lines 153-160. The used gridded temperature dataset includes uncertainties due to the
interpolation of the observed data. Have the authors considered how these uncertainties may
impact the results of their study?

We thank the editor for the comment. We added into the revised paper a more detailed description of the interpolation methods that Crespi et al. (2021) used and a quantification of the errors they obtained in a leave one out cross validation framework. The new sentence is reported here:

“This dataset is based on more than 200 station daily records which have been quality controlled and homogenized. The interpolation method is based on a combination of 30-year temperature climatology (1981–2010), daily anomalies and explicitly accounts for topographic features (i.e. elevation, slope) which are crucial in orographic complex areas such as the Trentino Alto-Adige. The leave one out cross validation presented in Crespi et al. (2021) finds mean correlation coefficient higher than 0.8 and mean absolute errors of around 1.5 degree Celsius (on average across months and stations used for the interpolation).”

Although the dataset is based on a state-of-the-art approach and the errors found in cross validation as relatively small, we added a new sentence in the conclusion section of the paper where we underline the importance of reducing the uncertainty in interpolating temperature data in orographically complex area. The new sentence is reported here:

“The hazard analysis presented in this paper rely on the Crespi et al. (2021) air temperature database. Although it is based on a state-of-the-art interpolation approach and it represents the best product for the area, more attention should be given to measuring meteorological variables in orographically complex area and at high elevation. This will in turn reduce the uncertainty in spatial interpolation and improve the quantification of impacting hazards such as HWs and CWs.”

4. In line 165, it is not clear how the cumulative indices are calculated and how someone can
interpret these indices. I assume that the HWMId is the sum of the daily magnitude of the
most severe heatwave in each year, something that is not clear in the manuscript.

We thank the reviewer for the comment. We have re-organized the section of the hazard definition according to the reviewer suggestions. Moreover, we also gave a practical example to explain what the index value means. The new sentence is:

“To quantify the hazard we used the HWMId (Russo et al., 2015) and the CWMId (Smid et al., 2019). These indices represent a way of measuring extreme temperature events while considering their durations, intensity, and taking in account the site-specific historical climatology (30years).

According to Russo et al. (2015), HWMId is defined as the maximum magnitude of the HWs in a year. A HW occurs when the air temperature is above a daily threshold for more than three consecutive days. The threshold is set to the 90th percentile of the temperature data of the day and the window of 15 days before and after throughout the reference period 1981-2010. The magnitude of a HW is the sum of the daily heat magnitude $\mathrm{HM_d}$ of all the consecutive days composing the HW (Equation 1):

$$\mathrm{HM_d}(\mathrm{T_d}) = \begin{cases} \dfrac{\mathrm{T_d} - \mathrm{T_{30y25p}}}{\mathrm{T_{30y75p}} - \mathrm{T_{30y25p}}} & \text{if } \mathrm{T_d} > \mathrm{T_{30y25p}} \\ 0 & \text{if } \mathrm{T_d} \leq \mathrm{T_{30y25p}} \end{cases} \tag{1}$$

where $HM_d(T_d)$ corresponds to the daily heat magnitude, T_d the temperature of the day in question and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile of the yearly maximum temperature for the 30 years of the reference period (1981-2010). The interquartile range (IQR, i.e. the difference between the T_{30y75p} and T_{30y25p} percentiles of the daily temperature) is used as the heatwave magnitude unit and represents a non-parametric measure of the variability of the temperature timeseries. Therefore, a value of $\mathrm{HM_d}$ equals to 3 means that the temperature anomaly on day d with respect to T_{30y25p} is 3 times the IQR. Finally, for a given year HWMId corresponds to the highest sum of magnitude (HMd) over the consecutive days composing a heatwave event (with only days with HMd > 0 considered).

Analogously to the HWMId, CWMId is defined as the minimum magnitude of the CWs in a year (Smid et al., 2019). A CW occurs when the air temperature is below a daily threshold for more than three consecutive days. The threshold is set to the 10th percentile of the temperature data of the day and the window of 15 days before and after throughout the reference period 1981-2010.

The daily cold magnitude corresponds to (Equation 2):

$$CM_d(T_d) = \begin{cases} \dfrac{T_d - T_{30y75p}}{T_{30y75p} - T_{30y25p}} & \text{if } T_d < T_{30y75p} \\ 0 & \text{if } T_d > T_{30y75p} \end{cases} \quad (2)$$

where $CM_d(T_d)$ corresponds to the cold daily magnitude, T_d the daily temperature and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile yearly temperature for the 30 years used as a reference. Inversely to HWMId, the lowest cumulative magnitude sum is retained for each year and with only consecutive days with $CM_d < 0$ considered to calculate it. CWMId being always <T 0, its absolute values are retained for its values to be on a positive interval (similar to HWMId)."

5. Line 215. What are exactly the outcomes of the Tweedie distribution? I assume it is only the return period. Please be more clear in the manuscript.

We thank the reviewer for the question. We add a new section where we specify the outcomes of the Tweedie distribution and the functions we used in the paper. This is connected to the next comment (6). The new sentence is:

"It provides distribution density, distribution function, quantile function, random generation for the Tweedie distributions. The Tweedie parameters (i.e. mean, power, and dispersion) have been estimated by the "tweedie.profile" function (Dunn, 2015) using the maximum likelihood as described by Dunn (2015) and Dunn and Smyth (2005)."

6. Lines 213-219. These lines need more analysis as they are essential for the computation of the return period. Also, the authors must include abbreviations for the legends in the Fig S-1

We thank you for the suggestion. We added the following new section to specify better how we fitted the Tweedie distribution and performed parameter estimation:

"It provides distribution density, distribution function, quantile function, random generation for the Tweedie distributions. The Tweedie parameters (i.e. mean, power, and dispersion) have been estimated by the "tweedie.profile" function (Dunn, 2015) using the maximum likelihood as described by Dunn (2015) and Dunn and Smyth (2005)."

Further we modified the figure S1, shortening the legends as requested by the reviewer and being more explicit in the caption to clarify the abbreviations used in the figure.

Old figure and caption:

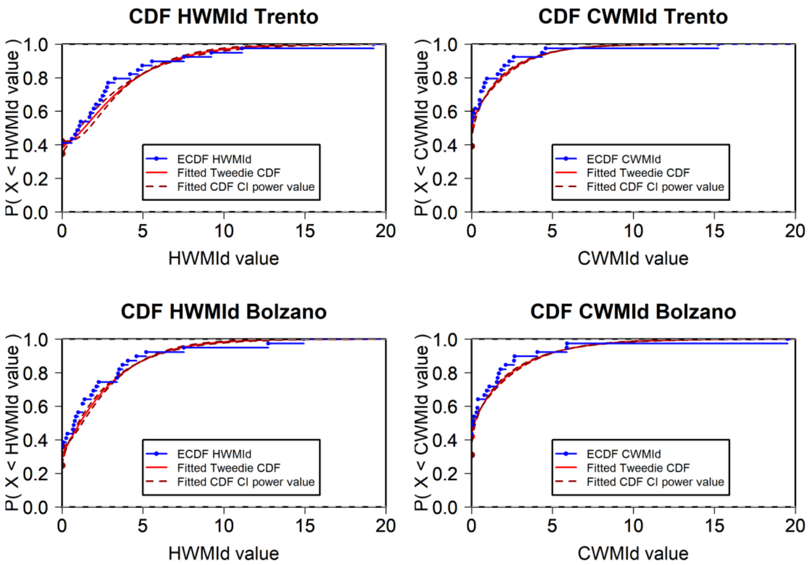


Figure S - 1: Cumulative distribution functions for both HWMId / CWMId at the location of the cities of Bolzano and Trento

The new figure and the new caption is reported below:

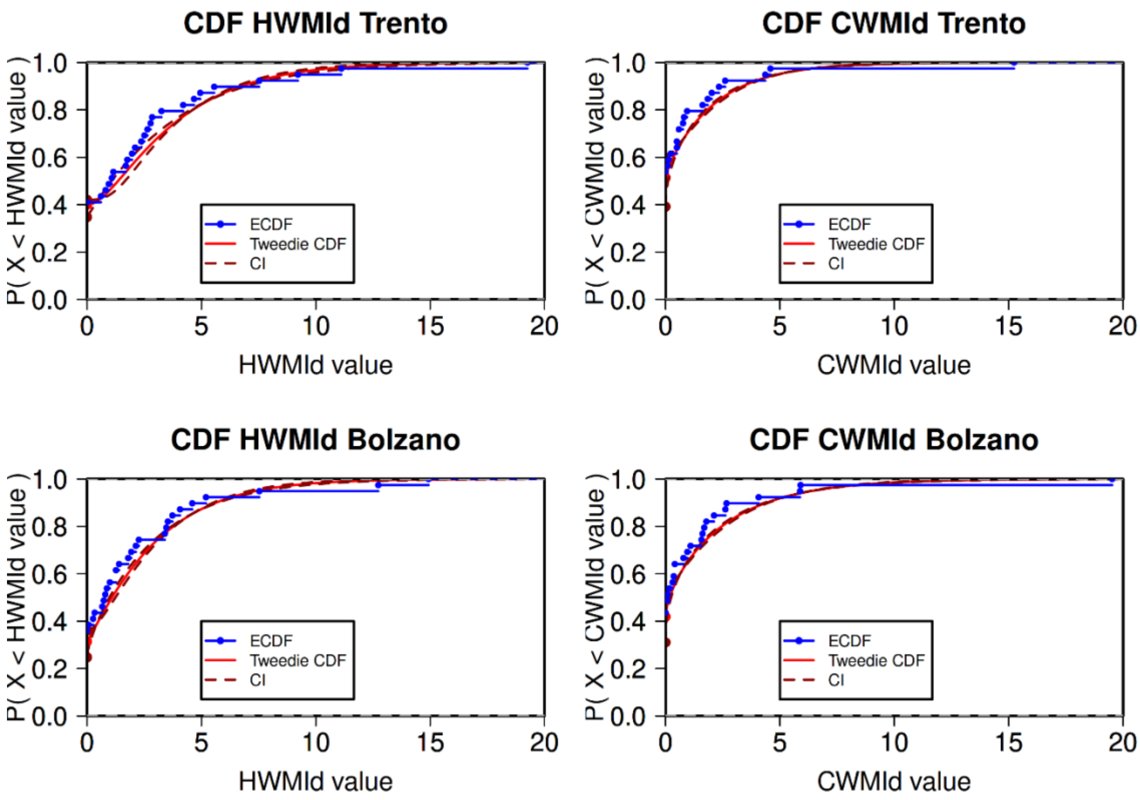


Figure S2: Cumulative distribution functions (CDF) for both HWMId / CWMId at the location of the cities of Bolzano and Trento, displaying the probability (P) showing the empirical cumulative distributions (ECDF) for these locations as well as the confidence interval (CI) of the power value of the Tweedie distribution.

7. Lines 218-219. Why have the authors chosen to keep only 5 and 10 return periods? Most
extreme episodes may fall into a higher return period (e.g. 20 or 30 return years)

We thank the reviewer for the comment. We choose 5 and 10 years return period for accounting of both the length of the analyzed return period (39 years) and the type of hazards we are analyzing (the HWs and CWs usually doesn't occur every year). Higher return periods estimations could be affected by higher extrapolation effects and more uncertainty.
We add the following sentence in the paper to clarify this point. The new sentence is:

"This choice aims to account for of both the length of the analyzed period (39 years) and the type of hazards we are analyzing (HWs and CWs usually doesn't occur every year). Higher return level estimations would be affected by extrapolation effects and higher uncertainty."

8. In line 253, the authors claim that the vulnerability is computed only for precise years while exposure has been calculated for each year. In line 275 the authors said that the computation of the risk was made based on the closest year. This limitation must be highlighted in the results (line 370 and further). Also, why the authors have chosen to use the "closest year" and not to interpolate the data?

We thank the reviewer for this question. We intensively revised this part of the paper. To account for the reviewer suggestion, we interpolated the data in time and removed the approximation of using the closest year (when possible) for all the variables (i.e. hazard, vulnerability and exposure).

The exposure data (i.e. population) are available for the years 1975, 1990, 2000 and 2015. We created yearly varying population maps following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018.

The vulnerability data are available for the years 1991, 2001, 2011. We created yearly varying vulnerability maps following the same approach we used for the population: we interpolated the data in time for the period 1991-2011 (assuming a constant rate in between available years) and we used the closest year for the period 1980-1990 and 2012-2018.

We added the following sentence in the section of the exposure:
"To more accurately model exposure, we created yearly varying population maps for the period 1980-2018 following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018."

We added the following sentence in the section of the vulnerability:

"Finally, we created yearly varying vulnerability maps for the period 1980-2018 following the same approach we used for the population."

9. Line 280. This section must be divided into subsections in an organized structure in order to be more clear and effective when presenting the findings of the paper. Also, the discussion
section must be clearer in order to defend your research and to emphasize the significance of
your research.

We thank you very much for this constructive feedback. To properly respond to this suggestion, we have re arranged the structure of the paper. We subdivided the results section in four specific subsections: 4.1) Hazard quantification and trends 4.2) Population exposure 4.3) Vulnerability quantification and 4.4) Risk quantification.

Finally, the discussion section has been separated from the result section and deeply reviewed to better emphasize as per the reviewer's comment. The new discussion section is:

The years found with the greatest HWs for the region agree with those of Russo et al. (2015), who found very high HWs in 1983, 2003 and 2015 in their analysis of the ten greatest HWs in Europe since 1950. The fact that four of the six largest HWs occurred in the last decade suggests that climate change is already influencing the intensity and frequency of HWs in the Trentino Alto-Adige region. With regards to CWs, Jarzyna & Krzyżewska, (2021), have also found cold spells in the years 1985 and 2012 using different methodologies for other locations throughout Europe. Similarly, other studies have found 1985 to be a year of an exceptional CW in Europe (Spinoni et al., 2015; Twardosz and Kossowska-Cezak, 2016).
The significant increasing trend we found in HWs events are consistent with other studies in Europe over the last decades (e.g. Perkins-Kirkpatrick and Lewis, 2020;

Piticar et al., 2018; Serrano-Notivoli et al., 2022; Spinoni et al., 2015; Zhang et al., 2020). The location of our highest increasing trends in HWs events are concordant to those of the higher increase in temperatures found at higher elevations by Acquaotta et al., (2015) in north-west Italy. Our results for HWs are also in line with the finding of Bacco et al., (2021) that analyzed trends in temperature extremes over northeastern regions of Italy (including Trentino Alto-Adige) based on homogenized data from dense station networks. They also found widespread warming, with significant positive trends in maximum-related mean and daytime temperature extremes. The lack of trend in CWs events is also in agreement with previous research that could not detect any trend in extreme cold spells (Jarzyna and Krzyżewska, 2021; Piticar et al., 2018).

The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016).

The two driving factors behind the increase in vulnerability (elderly population and isolation) have also been found as some of the main factors for vulnerabilities in other regions of Europe (López-Bueno et al., 2021; Poumadère et al., 2005). The results of our vulnerability analysis contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province. This contrast, between our finding and theirs, is related to the use of different indicators (employment, social-economic status, family structures, race/ethnicity, and population growth) and a different methodology for calculating the vulnerability where the normalization of indicators is applied across all of Italy in their study, as opposed to only over the Trentino Alto-Adige region in this study, the latter characterizing better local vulnerability. The selection of different indicators and methodology might yield different results.

Our findings related to the increase in HWs risks are consistent with Smid et al., (2019), which showed an increase of risk in both current and the future period for European capitals; the same study highlights a future decrease in CWs risk for these same cities. We found that CWs risk is still increasing for the main cities of our study.

This is also the case for other cities in mountainous regions, such as highlighted by López-Bueno et al. (2021) for the city of Madrid, where the urban area was found to be the more at CWs risk compared to the rural area.
The analysis of the trends of risk while changing only one of its three variables and keeping constant the remaining two shows that hazard and vulnerability are the main driving factor of the HWs risk. The changes in HWs risk due to hazard also highlights the presence of urban heat island in the most populated cities of the region (in Figure 6-e these are the zones of the highest increasing trends in risk). This has also been found in other in urban areas (e.g. Morabito et al., 2021). The changes in CWs risk is mainly explained by the demographic and vulnerability changes, which are increasing in/around urban areas and decreasing elsewhere.
The changes found in HWs and CWs risk due to changes in exposure or vulnerability only is partially explained by rural-urban migration and an aging population, which is presented in other studies such as (Reynaud and Miccoli, 2018).

Specific and minor comments:

1. Please insert the proper citations in lines 71-72.
Thank you for the comment. We added the new references. The old sentence in the paper was: "Most of these studies have found increasing trends in exposure to HW and for the studies that also analyzed CW, found decreasing trends for them."
The revised sentence reads:
"These studies found increasing trends in HWs (Chambers, 2020; Dosio et al., 2018) and decreasing trends in CWs in their period of analysis (Oldenborgh et al., 2019, Smid et al., 2019)."

2. Line 76: Is there an advantage to defining hazards by return period? Please add the information at the introduction or the methodology section.
We thank the reviewer for the question. We used the return period because it is a standard way to express extreme events intensity. The main novelty is that for the first time, we used the Tweedie zero inflated distribution to quantify the cumulative distribution function of the HWMId and CWMId, which are indeed zero inflated data.

3. There is a piece of misleading information in the citations in lines 136 and 162

We thank the reviewer for the comment. The sentence has been modified according to the reviewer's suggestion and is now consistent:

Old sentence: "The quantification of the hazard and its return period will be performed using the Heatwave magnitude index HWMId and its cold wave counterpart CWMId (Russo et al., 2014, 2015) "

New sentence:

1) Quantify HWs and CWs hazards and their return level at a very high spatial resolution (250m) by combining for the first time i) the indicators proposed by Russo et al., (2015) and Smid et al., (2019), together with ii) the Tweedie distribution;

4. Line 178. Please revise the sentence

We thank the reviewer for the suggestion. We revised the sentence according the reviewer suggestion. The new sentence has to be read in the context of the answer to the general comment 4.

Old sentence: "The highest cumulative magnitude is retained for each year and only consecutive days above 0 are considered when calculating it."

The new sentence is:

Finally, for a given year HWMId corresponds to the highest sum of magnitude (HMd) over the consecutive days composing a heatwave event (with only days with HMd > 0 considered).

5. Lines 189-190. Please revise the sentence

We revised the sentence according to the reviewer's suggestion.

Old sentence:

"For both the values of HWMId and CWMId to be positive and on the same interval, the absolute values of CWMId are retained from this point on."

New sentence:

"CWMId being always lower than zero, its absolute value is retained for its values to be on a positive interval (similar to HWMId)."

6. Lines 235-237. Please clarify better this sentence

We revised the sentence according to the reviewer's suggestion.

Old sentences: “Following recent studies (King and Harrington, 2018; Russo et al., 2019), for each year of the time period a pixel is considered exposed if the HW/CW hazard (measured by HWMId or CWMId) is greater than zero or a specified return level value. For that year, the population exposed in the region is the sum of all exposed pixels in the region. The percentage of population exposed is obtained dividing the population exposed by the total population in the region at that time. The results for the percentage of population exposed are calculated on annual basis over the study period (1980-2018).

New sentences:

Following recent studies (King & Harrington, 2018; Russo et al., 2019), for each year, a pixel is considered exposed to HW/CWs hazard (or to a 5 or 10 year return-period HWs/CWs) if for that year the HWMId/CWMId of the pixel is greater than zero (or greater than the corresponding return level HW5Y/CW5Y or HW10Y/CW10Y, respectively).This is the exposition factor, and it is a binary value (0 meaning not exposed or 1 meaning exposed).

The percentage of population exposed are calculated on annual basis over the study period (1980-2018) with the help of population data linearly interpolated from 1980 to 2018.

Using this population data, percentage of population exposed are then calculated using the following equation (Equations 5 and 6):

$$Population\ exposed(t) = \sum_i EF_i * population_i(t) \quad (5)$$

$$Percentage\ of\ population\ exposed\ (t) = \frac{Population\ exposed(t)}{Total\ population\ (t)} \quad (6)$$

where i corresponds to the pixels, t to the year being analyzed, EF to the exposition factor mentioned above (binary).

7. Line 255. Please elaborate on this

We thank the reviewer for the suggestion. We extended the sentence and modified it according to the reviewer’s comment.

Old sentence:” The methodology to quantify vulnerability uses the equal weight analysis (EWA, e.g. Liu et al, 2020)”

New sentence:

"The methodology to quantify vulnerability uses the equal weight analysis (EWA, e.g. Liu et al, 2020). Firstly, the individual indicators are standardized between 0 and 1, prior to aggregation (their sum); the standardization is done at the city level for all the years of record (1991, 2001, 2011) based on Equation 7:

$$\text{Standardized Indicator }(t) = \frac{\text{Indicator}(t) - \min\left(\text{Indicator}_{1991,2001,2011}\right)}{\max\left(\text{Indicator}_{1991,2001,2011}\right) - \min\left(\text{Indicator}_{1991,2001,2011}\right)} \quad (7)$$

Secondly, the EWA is performed according to Equation 8:

$$\text{Vulnerability }(t) = \frac{\sum \text{Standardized indicator(t)}}{\text{number of indicators}} \quad (8)$$

This approach was chosen as it is the simplest method for weighing the vulnerability indicators and it is commonly applied in the literature with regards to HWs and CWs (e.g. Buscail et al., 2012; Buzási, 2022)."

8. Line 269. It is not clear in the manuscript how the hazard is defined

We revised according to the reviewer suggestion.

The old sentence was:

"Hazard is the probability of HWMId/CWMId derived from the Tweedie distribution"

The new sentence is:

"The hazard is computed as the probability of occurrence of HWs/CWs by using the fitted Tweedie distributions probability function for each pixel."

9. Line 282. Why have the authors chosen the median and not the mean for the intensity of the HW?

The median was chosen to avoid the possibility of a particular high or low intensity area affecting the overall result.

10. Line 343. The authors must comment on the uncertainty in increasing and decreasing values found for vulnerability. Also, they must highlight that these trends

are not statistically
significant.

We thank the reviewer for the suggestion we added the following sentence to the discussion section:

The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016).

11. Fig 4. The vulnerability is calculated for hw or cw?

The vulnerability is calculated for extreme temperatures so both hw and cw Several other studies used the same approach, see for example the methodology used in Nwoko (2016) and Török et al. (2021).

Nwoko, D. S. V. I. for E. T. R. in N.: Developing social vulnerability index for newcastle extreme temperatures, Msc Thesis, Durham University, 68 pp., 2016.

Török, I., Croitoru, A.-E., and Man, T.-C.: Assessing the Impact of Extreme Temperature Conditions on Social Vulnerability, Sustainability, 13, 8510, https://doi.org/10.3390/su13158510, 2021.

12. Line 413. “HW have occurred more frequently and have become more intense”. This
sentence is not properly justified in the results section.

We agree with the reviewer comment, and we rephrased the sentence.

The sentence old sentence was: HW have occurred more frequently and have become more intense.

The new sentence is: “HWs, i.e. HWMId>0, (and extreme HWs, i.e. HWMId>HW5Y) showed increasing trends in most of the region, with 98% (70%) being statistically significant.”

13. Line 417. Please rephrase in order to highlight the limitations of this result

We thank the reviewer for the comment. In the new revised paper this part have been moved in the discussion section and it has been rephrased according to this comment.

The old sentence was:
“In general, vulnerability is decreasing over time in the Trentino Alto-Adige region. However, in the larger cities of the region, vulnerability is increasing due to an ageing population and more single households. It should be noted that the socioeconomic indicators of vulnerability are only available for three points in time, which does not allow to do a proper trend analysis of vulnerability”

The new sentence in the discussion section is:
“The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016).”

14. Line 428. Why “will be exposed”? This work is not a future projection analysis
We revised the sentence according to the reviewer suggestion. The old sentence was:
“The findings of this work shows that municipalities and cities in the Trentino Alto-Adige region, but likely also in many other regions, will be exposed especially to more frequent and intense heat, while potentially still experiencing the same levels of cold wave hazard”
The revised sentence is:
“The findings of this work shows that municipalities and cities in the Trentino Alto-Adige region have been seen increasing trends in HWs risk over the timeframe 1980-2018, while potentially experiencing the same levels of CWs risk.”

Answer to the reviewer 2

The paper went through a deep revision in which we: i) revised the language, ii) modified the paper structure (separating the discussion section from the result section, highlighting the main finding in the conclusion section), iii) improved the abstract, introduction, and methodology sections, iv) we changed and improved the figures' quality and captions.

Finally, we extended the level of discussion and we added more citation to justify and compare with our findings.

Moreover, we added the new analysis requested by the reviewer n1 and n. 2, specifically:

d) As both the reviewer asked, we used the methodology of linear interpolation in time instead of the closest-year method presented in the original version of the paper
e) to disentangle the effect of each single components of the risk on its total changes, changing in turn one by one each element (i.e. vulnerability, exposure and hazard) and keeping constant the other two
f) finally we also improved our trend analysis and statistical significancy evaluation by using the FDR methodology.

Answers to the Reviewer 2

General comments

This study investigates and quantifies hazard, exposure, and vulnerability to heat and cold extremes in the Italian region Trentino Alto-Adige for 1980-2018 and calculates the resulting combined risk. The structure of the paper is generally clear, and the presented results are mostly convincing. My main comments concern 1) the language, 2) a more precise estimation of the contribution of hazard, exposure, and vulnerability to the overall risk, 3) extending the figure captions, and 4) adjusting the p-values of the statistical significance tests to control for the false discovery rate.

We thank the reviewer for the revision and the useful comments and insights. We reviewed the paper according to the suggestions and below you can find a one-to-one answer. The answer to the reviewer comments are provided in red, the new revised sentences are provided in blue.

Main comments:

Although the manuscript is generally well comprehensible, the structure of some sentences and some of the terms that are used make some parts difficult to understand. I would thus recommend to carefully check the whole text again with a special focus on rephrasing cumbersome sentences (some examples are listed under “specific comments”)

We revised the manuscript and its organization as well as the results presentation, discussion, and conclusions. All the specific comments have been implemented in the revised paper.

I think that it would be possible to calculate the contribution of changes in hazard, exposure, and vulnerability to the overall changes in risk ratio (e.g. by keeping exposure constant while changing the other parameters, and similarly for the other parameters). I think this could provide a valuable insight into the importance of climate change vs population and socioeconomic changes.

We implemented the analysis requested by the reviewer, we provided a new figure summarizing the result of this analysis and we added the following new sentences in the revised paper.

The new figure is the following:

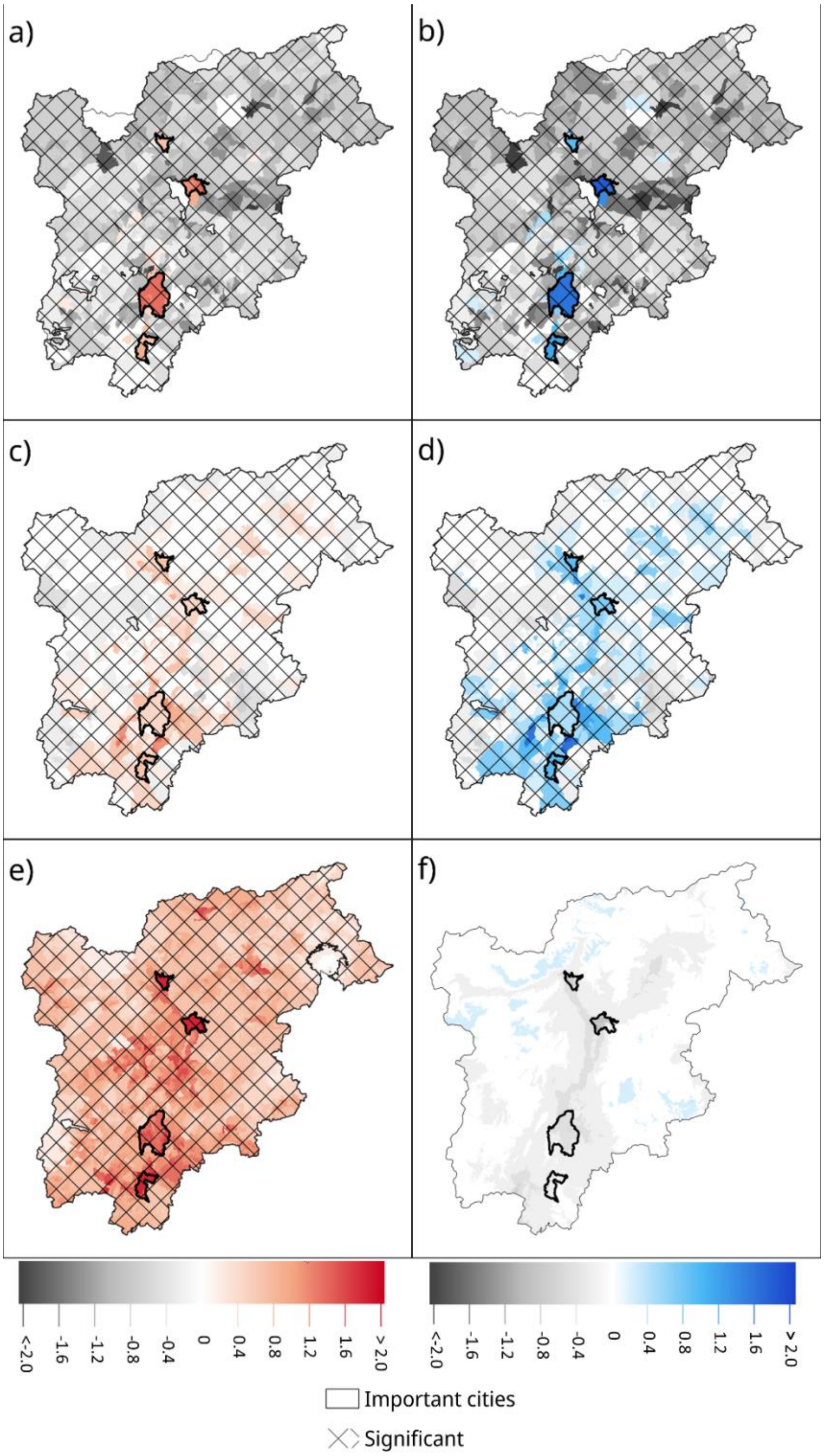


Figure 6: Trends of heat waves (and cold waves) risks due to changes in: a (b) vulnerability only, c (d) exposure only, and e (f) hazard only. Trends found with the robust linear method, colors indicating an increase in the risk and grey a decrease, significance is indicated with the hashing, the yearly change being the robust linear model coefficient.

The new sentences added in the result section are the following:

"Figure 6 shows the marginal effect of the driving factor behind the trends in HWs and CWs risks. Figure 6-a, Figure 6-c, and Figure 6-e (Figure 6-b, Figure 6-d, and Figure 6-f) show the trend in HWs (CWs) risks with only vulnerability, only exposure, and only hazard changing, respectively.
The results in Figure 6-a and Figure 6-b show the same patterns as well as Figure 6-c and Figure 6-d because exposure and vulnerability are the same for both HWs and CWs and hazard is the only differing variable.
Figure 6-a (Figure 6-b) show increasing trends in risk (due to change in vulnerability only) in the main cities and nearby areas. Decreasing trends are found for most of the remaining region.
Figure 6-c (Figure 6-d) show increasing trends in risk (due to change in exposure only) in/near urban areas and decreasing trends in zones at high elevations and far from the urban centers.
Figure 6-d show that the hazard is the main driver of risk for HWs, with statistically significant increasing trends, more evident in and around highly populated areas. Finally, Figure 6-e show no significant trends in CWs risk (due to change in hazards only)."

The new sentences added in the discussion section are the following:

The analysis of the trends of risk while changing only one of its three variables and keeping constant the remaining two shows that hazard and vulnerability are the main driving factor of the HWs risk. The changes in HWs risk due to hazard also highlights the presence of urban heat island in the most populated cities of the region (in Figure 6-e these are the zones of the highest increasing trends in risk). This has also been found in other in urban areas (e.g. Morabito et al., 2021). The changes in CWs risk is mainly explained by the demographic and vulnerability changes, which are increasing in/around urban areas and decreasing elsewhere.
The changes found in HWs and CWs risk due to changes in exposure or vulnerability only is partially explained by rural-urban migration and an aging population, which is presented in other studies such as (Reynaud and Miccoli, 2018).

The captions of the figures are currently very short and contain insufficient information to fully understand the associated figures. A caption should be written such that it is possible to understand a figure and its main message only from watching the figure and reading its caption (i.e., without the need to read the main text). I would thus recommend extending the captions such that they explain the figures and the displayed features more comprehensibly.

Thank you, this has been considered and the captions have been rewritten accordingly. Please, see also the specific comments where we show the modification.

Many of the figures contain estimates of statistical significance. As the multiple statistical tests (which I presume are conducted independently for each grid cell) may cause to overestimate the statistical significance (Wilks, 2016, https://doi.org/10.1175/BAMS-D-15-00267.1), I would suggest adjusting the p-values by controlling for the false discovery rate as proposed by Wilks (2016).

Thank you for this suggestion, all the figures have been remade with this suggestion, their significance corresponds to the FDR significance. Moreover, we added the following new section in which we explained the methodology we used.

The new sentence is:

The trends are analyzed using the robust regression technique (Huber, 2011). This method is often used throughout the literature for natural hazards (Formetta and Feyen, 2019; Kishore et al., 2022).

The trends are analyzed using the robust regression technique (Huber, 2011). This method is often used throughout the literature for assessing trends in natural hazards (Formetta and Feyen, 2019 for multiple hazards and Kishore et al., 2022 specifically for HWs). To confirm the statistical significance of the trends the false discovery rate (FDR) methodology is used according to Wilks (2016) and Leung et al. (2019), with a significance level α=0.05. The FDR is defined as the statistically expected fraction of null hypothesis test rejections at the grid cell for which the respective null hypotheses are actually true (Wilks 2016).

Specific comments:

1 Lines 15-16 (and generally for the description of the Tweedie distribution): I think it would make sense to first mention that HWMId and CMWId are normalized to the interval (0, 1) to combine them with the exposure and vulnerability metrics, and only then write that the Tweedie distribution is used for this purpose.

Thank you this has been adjusted. The old sentence was:

We use the Heat Wave Magnitude Index daily (HWMId) and a Cold Wave Magnitude Index daily (CWMId) as temperature-based indicators and apply a Tweedie zero-inflated distribution to derive hazard intensities and frequencies. The hazard maps are combined with high-resolution maps of population, for which the vulnerability is quantified at community and city level using a set of eight socioeconomic indicators.

The new sentence is:

To obtain HWs and CWs risk maps we combined: i) occurrence probability maps of the hazard, ii) normalized population density maps, and iii) normalized vulnerability maps based on eight socioeconomic indicators. The occurrence probability of the hazard is obtained using the Tweedie zero-inflated distribution. The methodology allowed us to disentangle the effects of each component of the risk to its total change.

2 Line 17: Maybe better "which are used to derive vulnerability"

Thank you for this suggestion, this sentence has been rephrased entirely as part of the changing of the abstract. See the sentence above.

3 Line 18 ff: I am wondering how the increased resilience is determined? Maybe the factors causing the increased resilience could be mentioned here (same for CW)

We thank the reviewer for the suggestion, the sentence was actually removed in order to make the abstract shorter per the other reviewer's request, only the trends in vulnerability are now mentioned.

The old sentence was: "We observe a general trend towards increased resilience to extreme temperature spells over the region. In the larger cities of the region, however, we find that vulnerability has increased due to an ageing population and more single households."

The new revised sentence is:

"A decrease in vulnerability to extreme temperature spells is observed trough the region except in the larger cities where vulnerability has increased."

4 Line 36 (and other occasions): I think that the text would be easier to read if an "s" would be added to the acronyms for the plural forms of "heat wave" and "cold wave" (i.e., HWs, CWs).

We thank the reviewer for the suggestion, we adjusted it throughout the entire text.

5 Line 38: In which direction do they change? Increasing or decreasing?

We thank the reviewer for the question. We revised the section. The old section "With global warming, heat and cold wave intensities and durations are expected to change (Perkins-Kirkpatrick and Gibson, 2017; Russo et al., 2015; Smid et al., 2019), which could increase the risks to society."

The new revised sentence is:

"With global warming, HWs intensities and durations are expected to increase while those of CWs are expected to decrease (Perkins-Kirkpatrick and Gibson, 2017; Russo et al., 2015; Smid et al., 2019), which would change their risks to society."

6 Line 42: How are heatwaves defined in this study? Based on percentiles? Or is it HWMId?

We thank the reviewer for the question. Heatwave in that study are defined as 3days above the 90th percentile temperature. This is now mentioned in our article and the new sentence is:

"In Europe, recent high intensity HWs events (2003 and 2018, where HWs are defined as 3 days over 90th temperature percentile of the 1980-2010)."

7 Line 43-44: This part of the sentence about GCP losses is a bit difficult to understand. I would suggest rephrasing it.

The sentence about the GDP has been removed in our attempt to make the introduction a bit shorter and straightforward as suggested by both reviewers.

8 Line 71-73: Rephrase, as the last part reads rather cumbersome.

We thank the reviewer for the suggestion. The sentence has been rephrased. The old sentence was:
"Most of these studies have found increasing trends in exposure to HW and for the studies that also analyzed CW, found decreasing trends for them."
The new sentence is:
"These studies found increasing trends in HWs (Chambers, 2020; Dosio et al., 2018) and decreasing trends in CWs in their period of analysis (Oldenborgh et al., 2019, Smid et al., 2019)."

References were added as per the other reviewer's request.

9 Line 99: Maybe "are most exposed to" instead of "affect"
We thank the reviewer for the question, we revised the sentence. The old sentence was:
"In Korea at the county level, Kim et al. (2017) found that elderly living alone, agricultural workers and unemployed affect vulnerability to heat wave days and tropical nights"
The new revised sentence is:
"In Korea at the county level, Kim et al. (2017) found that elderly living alone, agricultural workers, and unemployed are the most significant vulnerability factors to extreme temperatures."

10 Line 113-114: What does "normalized population" mean? Can this be shortly explained here?
We thank the reviewer for the question, and we revised the sentence. Russo et al., 2019 normalized the population density maps in order to have values between 0 and 1 and therefore consistent with the hazard (between 0 and 1) and the vulnerability (between 0 and 1) in the risk equation.
The old sentence was: "where the exposure is the normalized population".
The new sentence is: "where the exposure is the population density normalized in [0;1] based on its maximum, minimum values;"

11 Line 134: Remove "for the"
We thank the reviewer for the suggestion, and we removed it.

The old sentence was:

"The aim of this article is to solve some of these previous limitations while quantifying heat and cold waves hazards, the human exposure, vulnerability, and risk for the at the high-definition city scale for the Trentino-Alto-Adige region over the period 1980-2018"

The new revised sentence is:

"The aim of this article is to solve some of these previous limitations while quantifying HW and CW hazards, the human exposures, vulnerabilities, and risks at the high-definition (i.e. city-scale) over the period 1980-2018, for the Trentino-Alto-Adige region"

12 Lines 141-143: Something with the reference to Figure 1 is wrong

We thank the reviewer for the comment. We have addressed revising the sentence.

The old sentence was:

"The Trentino Alto-Adige region (**Error! Reference source not found.**) is a mountainous region in northern Italy, which borders Austria"

The new revised sentence is:

"The Trentino Alto-Adige region (Figure 2) is a mountainous region in northern Italy, which borders Austria"

13 Lines 145-146: I think it would be good to exactly state the population of Trento, Bolzano, Merano and Rovereto

We thank the reviewer for the suggestion. We revised the sentence accordingly. The old sentence was: "Its most populous cities are the two provincial capitals -Trento and Bolzano - as well as minor cities Merano and Rovereto (both have a population of over 30000)"

The new revised sentence is

Its most populous cities (population for 2022 in parenthesis) are the two provincial capitals, Trento (118509) and Bolzano (107025), as well as minor cities such as Merano (40994) and Rovereto (39819).

14 Lines 157-160: I think it would be good to shortly explain which variables are used for the extrapolation of the temperature dataset (e.g. height, land cover, something else?)

We thank the reviewer for the question. We revised this section including more information on the interpolation schema (and on the geomorphological variables used in the interpolation).

The old sentence was:

"The dataset is obtained with the anomaly-based approach taking into account elevation of the local station observations; the dataset has undergone a quality analysis and control against the stations' observations (Crespi et al. 2021)."

The new revised sentence is:

"This dataset is based on more than 200 station daily records which have been quality controlled and homogenized. The interpolation method is based on a combination of 30-year temperature climatology (1981–2010), daily anomalies and explicitly accounts for topographic features (i.e. elevation, slope) which are crucial in orographic complex areas such as the Trentino Alto-Adige. The leave one out cross validation presented in Crespi et al. (2021) finds mean correlation coefficient higher than 0.8 and mean absolute errors of around 1.5 degree Celsius (on average across months and stations used for the interpolation)."

15 Lines 164ff: What is the reference period for calculating HWMId? I would also explicitly mention that data are pooled from a window of 15 days before and after each day (currently this is not entirely clear).

We thank the reviewer for the question. We revised the sentence better specifying the reference period for calculating HWMId. The old sentence was:

For HWMId, from the temperature time series in each grid cell, we select the days where the temperature is above the 90th percentile of the dataset Ad (Equation 1):

$$A_d = \bigcup_{y=1981}^{2010} \bigcup_{i=d-15}^{d+15} T_{y,i}$$

(1)

where y corresponds to the year, i to the day, and Ty,i correspond to the temperature of the corresponding year and day and the dataset Ad corresponds to the temperature data for 30 years, centered on a 31-day window for the day in question. Three consecutive days above this threshold correspond to a HW.

The new revised sentence is:

According to Russo et al. (2015), HWMId is defined as the maximum magnitude of the HWs in a year. A HW occurs when the air temperature is above a daily threshold for more than three consecutive days. The threshold is set to the 90th percentile of the temperature data of the day and the window of 15 days before and after throughout the reference period 1981-2010.

16 Line 175: I think rather “daily heat magnitude”

We thank the reviewer for the suggestion. We revised the sentence accordingly.

The old sentence was: “to the heat daily magnitude.”

The new revised sentence is: “the daily heat magnitude.”

17 Line 176: Are the percentiles calculated from the temperature distribution or from the yearly maximum temperatures? (the latter is done in the original publication by Russo et al.).

We thank the reviewer for the question. We used the yearly maximum temperatures, and we revised the sentence accordingly.

The old sentence was:

“where HMd(Td) corresponds to the heat daily magnitude, Td the temperature of the day in question and T30y25p and T30y75p correspond to the 25th and 75th percentile temperature for the 30 years used as a reference”

The new revised sentence is:

where $HM_d(T_d)$ corresponds to the daily heat magnitude, T_d the temperature of the day in question and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile of the yearly maximum temperature for the 30 years of the reference period (1981-2010).

18 Line 178: I would write “only consecutive days with HMd above 0”

We thank the reviewer for the suggestion. We modified the sentence (and the entire paragraph to describe the HWMId in a more clear way). The old sentence was:

“The highest cumulative magnitude is retained for each year and only consecutive days above 0 are considered when calculating it”.

The new revised sentence is:

Finally, for a given year HWMId corresponds to the highest sum of magnitude (HMd) over the consecutive days composing a heatwave event (with only days with HMd > 0 considered).

19 Line 189-190: I think it would be good to explicitly write that based on the definition used in this paper, CMd is always <0

We thank the reviewer for the question. We revised the sentence according to the suggestion. The old sentence was:

"Similarly, the lowest cumulative magnitude is retained for each year and only consecutive days below 0 are considered when calculating it. For both the values of HWMId and CWMId to be positive and on the same interval, the absolute values of CWMId are retained from this point on."

The new revised sentence is:

Inversely to HWMId, the lowest cumulative magnitude sum is retained for each year and with only consecutive days with $CM_d < 0$ considered to calculate it. CWMId being always <T 0, its absolute values are retained for its values to be on a positive interval (similar to HWMId).

20 Lines 210-212: This is partly a repetition, maybe shorten it?

We thank the reviewer for the suggestion, we have removed the sentence accordingly.

Line 220ff: I would suggest writing more specific what the KS test has been used for in this paper ("statistical fit verification" sounds rather generic)

We thank the reviewer for the suggestion. We modified the sentence accordingly.

Old sentence: "For statistical fit verification, the Kolmogorov–Smirnov (KS) test on two samples is used with one sample being the found HWMId or CWMId values, and the other sample being a randomly generated sample using the fitted distribution value."

New revised sentence.

"The goodness of fit of the Tweedie distribution fitted to the HWMId/CWMId data for every pixel have been tested by means of a Kolmogorov-Smirnov test of hypothesis.

The test is performed using two samples, with the first being the data and the other being a randomly generated sample using the fitted distribution parameters.

21 Line 230: "population data"

We thank the reviewer for the suggestion. We modified the sentence accordingly.

Old sentence: "To quantify the population exposed to HW and CW we use time-varying population from the Global Human Settlement Layer (GHSL) (Schiavina et al., 2019). The data is available at a resolution of 250m for the following years: 1975, 1990, 2000 and 2015:"

New revised sentence: "To quantify the population data exposed to HWs and CWs, we use time-varying population data from the Global Human Settlement Layer (GHSL) (Schiavina et al., 2019). The population data is available at a resolution of 250m for the following years: 1975, 1990, 2000 and 2015".

22 Lines 254-256: This sentence is not clear to me. Could it be explained a bit more in detail how this was done and why this approach was chosen?

We clarified better this concept in the revised paper. Equation 8 and 9 have been added as well as paragraph mentioning why this methodology was picked.

The old sentence was: "The methodology to quantify vulnerability uses the equal weight analysis (EWA) with the indicators being standardized between 0 and 1 prior to aggregation according to Liu et al, (2020)."

The new revised sentence is:

The methodology to quantify vulnerability uses the equal weight analysis (EWA, e.g. Liu et al, 2020). Firstly, the individual indicators are standardized between 0 and 1, prior to aggregation (their sum); the standardization is done at the city level for all the years of record (1991, 2001, 2011) based on Equation 7:

$$\text{Standardized Indicator } (t) = \frac{\text{Indicator}(t) - \min\left(\text{Indicator}_{1991,2001,2011}\right)}{\max\left(\text{Indicator}_{1991,2001,2011}\right) - \min\left(\text{Indicator}_{1991,2001,2011}\right)} \quad (7)$$

Secondly, the EWA is performed according to Equation 8:

$$\text{Vulnerability } (t) = \frac{\sum \text{Standardized indicator(t)}}{\text{number of indicators}}$$

(8)

This approach was chosen as it is the simplest method for weighing the vulnerability indicators and it is commonly applied in the literature with regards to HWs and CWs (e.g. Buscail et al., 2012; Buzási, 2022).

Finally, we created yearly varying vulnerability maps for the period 1980-2018 following the same approach we used for the population.

23 Lines 274-279: Another approach could be the temporal linear interpolation of the exposure and vulnerability variables.

We thank the reviewer for this question. We intensively revised this part of the paper. To account for the reviewer suggestion, we interpolated the data in time and removed the approximation of using the closest year (when possible) for all the variables (i.e. hazard, vulnerability and exposure).

The exposure data (i.e. population) are available for the years 1975, 1990, 2000 and 2015. We created yearly varying population maps following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018.

The vulnerability data are available for the years 1991, 2001, 2011. We created yearly varying vulnerability maps following the same approach we used for the population: we interpolated the data in time for the period 1991-2011 (assuming a constant rate in between available years) and we used the closest year for the period 1980-1990 and 2012-2018.

We added the following sentence in the section of the exposure:

"To more accurately model exposure, we created yearly varying population maps for the period 1980-2018 following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018.."

We added the following sentence in the section of the vulnerability:

“Finally, we created yearly varying vulnerability maps for the period 1980-2018 following the same approach we used for the population.”

24 Line 303: Here, does HW mean the yearly HWMId values or something else? Could that be specified?

We thank the reviewer for the suggestion. Yes it is correct and we modified the sentence accordingly. Old sentence:” statistically significant positive trends are found for HW in most pixels of the region (Figure 2)”

New revised sentence: “Fitting the robust linear model to the HWs values, statistically significant positive trends are found for HWs (i.e. HWMId > 0) and HWs with a magnitude larger than the 5-year event (HWMId > HW5Y) in most pixels of the region (Figure 2).”

25 Line 305-306: If I understand correctly, there should only be 3-4 values for HW10Y in each pixel, given that a period of 39 years is used. I am not sure whether a trend can be deduced from such few data points.

We agree with the reviewer comment. We used the robust regression method and the FDR method to evaluate the trend in a more robust way. For very exteme heatwave hazard in the revised paper we obtain as result no statistical significance (with FDR).

26 Line 312: Maybe “that was” instead of “and”?

Thank you, this sentence has been removed in the revised paper.

27 Lines 324-328: I would add “event” after HW and CW.

Thank you, we modified accordingly. However this section is now in the discussion section.

The old sentence was: “The significant increasing trend for HW that we find are consistent with literature that reported increasing HW trends in Europe over the last decades (Perkins-Kirkpatrick and Lewis, 2020; Piticar et al., 2018; Serrano-Notivoli et al., 2022; Spinoni et al., 2015 Zhang et al., 2020). The lack of trend in CW is also in agreement with previous research that could not detect any trend in extreme cold spells (Jarzyna and Krzyżewska, 2021; Piticar et al., 2018)"

The new revised sentence is: "The significant increasing trend we found in HWs events are consistent with other studies in Europe over the last decades (e.g. Perkins-Kirkpatrick and Lewis, 2020; Piticar et al., 2018; Serrano-Notivoli et al., 2022; Spinoni et al., 2015; Zhang et al., 2020). The location of our highest increasing trends in HWs events are concordant to those of the higher increase in temperatures found at higher elevations by Acquaotta et al., (2015) in north-west Italy. Our results for HWs are also in line with the finding of Bacco et al., (2021) that analyzed trends in temperature extremes over northeastern regions of Italy (including Trentino Alto-Adige) based on homogenized data from dense station networks. They also found widespread warming, with significant positive trends in maximum-related mean and daytime temperature extremes. The lack of trend in CWs events is also in agreement with previous research that could not detect any trend in extreme cold spells (Jarzyna and Krzyżewska, 2021; Piticar et al., 2018)."

28 Lines 329-331: But Figure 3 does not present a separation of both effects! It shows the combined effects of changes in HWs and of changes in population. I think that for disentangling both effects, one of them would need to be kept constant (see also main comment above)

We implemented this change in the revised paper. See the main comment above to view the new figure and new sentences added in result and discussion sections.

29 Line 350: Not sure that "extreme age" is the right term.

We thank the reviewer for the suggestion, we modified accordingly. Old sentence: "The increase in these cities' vulnerability relates to the extreme age indicator and social status,"

New revised sentence: "The increase in these cities' vulnerability relates to the older age indicator and social status"

30 Line 360: I would delete "somehow"

We thank the reviewer for the suggestion, and we modified that sentence accordingly from: The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province.

The new sentence is: The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province.

31 Lines 362-365: Does this refer to the study by Frigerio & De Amicis?

We thank the reviewer for the comment, and have clarified this aspect in a clearer way. This refers to the difference between the two (our study and theirs) and has been specified. This part is now in the discussion. The old sentence was:

Old sentence was:

“The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province. This likely relates to the use of different indicators (employment, social-economic status, family structures, race/ethnicity, and population growth) and a different methodology for calculating the vulnerability. Notably in Frigerio & De Amicis (2016) the normalization of indicators is applied across all of Italy as opposed to only over the Trentino Alto-Adige region in this study, which may better characterize local vulnerability.”

The new revised sentence is:

“The results of our vulnerability analysis contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province. This contrast, between our finding and theirs, is related to the use of different indicators (employment, social-economic status, family structures, race/ethnicity, and population growth) and a different methodology for calculating the vulnerability where the normalization of indicators is applied across all of Italy in their study, as opposed to only over the Trentino Alto-Adige region in this study, the latter characterizing better local vulnerability. The selection of different indicators and methodology might yield different results.”

32 Lines 368-372: These results cannot easily be seen in the figures. I would suggest to change the figures to make this better visible (see my comments to Figure 5 below)

We thank the reviewer for the comment and have remade the figure in order to make the results more evident. The difference is shown in the comment about the figure below.

33 Lines 377-380: What are the main factors? Can they be identified, and can their contribution be quantified? (see also my main comment above)

Following your main comment a further analysis has been conducted and the results are discussed in the appropriate section and are visible in Figure 6. See also the reply to the main comment above

34 Line 407: Mainly "normalized" instead of "sized"

We thank the reviewer for the suggestion. We use hazard quantification. The new sentence is:

"The hazard probability of occurrences are then quantified by fitting a Tweedie distribution to the HWMId and CWMId values, explicitly accounting for zero values in their time series"

35 Line 409: I do not really understand the meaning of this sentence.

We thank the reviewer for the comment and have revised the sentence accordingly.

Old sentence: "Exposure is be found using the different fitted hazard levels."

New sentence: "Two types of population exposure are found using the different hazard levels (5 years and 10 years return level)."

36 Line 428: Are there any proofs/studies showing that this is the case "likely also in many other regions"? Otherwise this statement should be deleted.

We thank the reviewer for the comment, and we deleted the sentence accordingly.

Figures:

1. Figure 1: I think it would be good to have some more information in the caption, e.g. that Merano, Bolzano, Trento, and Rovereto are the main cities in the region and what the colors mean.

We thank the reviewer for the comment we added more information as quested. The old caption was: Figure 1: The Trentino Alto-Adige region

The new caption is: Figure 2: The Trentino Alto-Adige region and its most populated cities (Trento, Bolzano, Rovereto and Merano); the colors indicating the elevations, river network, and lakes.

"

2. Figure S-1: The abbreviations used in the legends and the titles should be explained in the caption.

Thank you, we modified the figure and the caption accordingly.

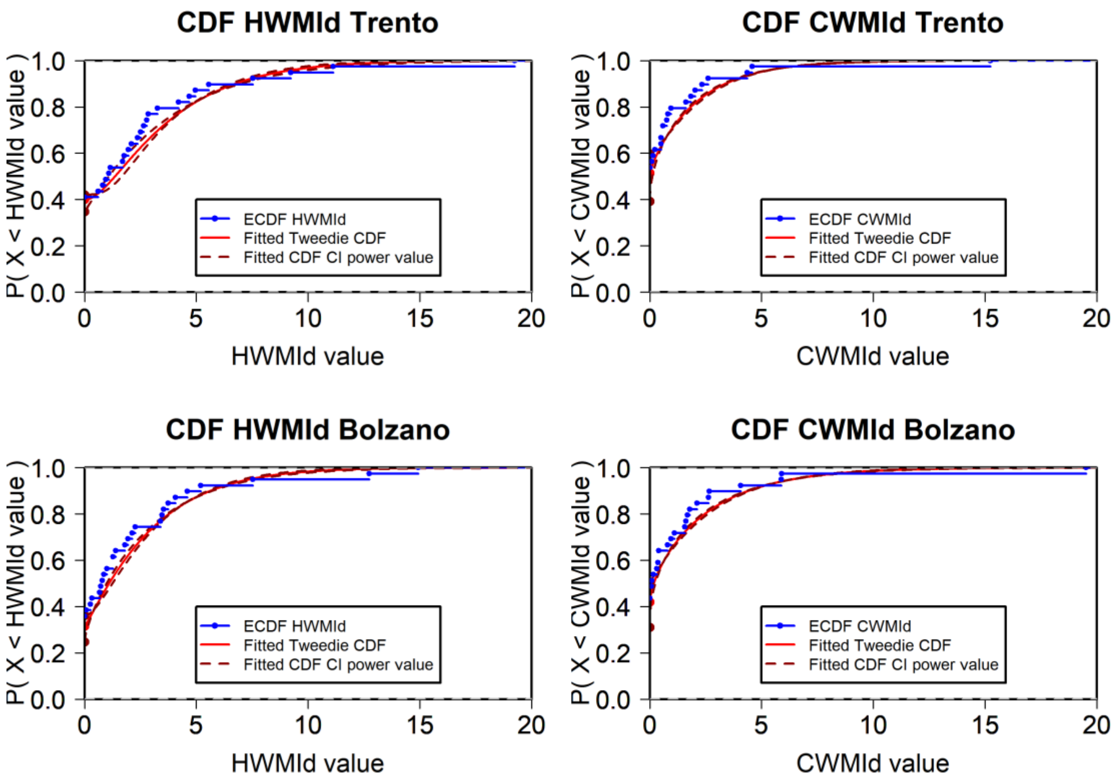


Figure S - 3: Cumulative distribution functions for both HWMId / CWMId at the location of the cities of Bolzano and Trento

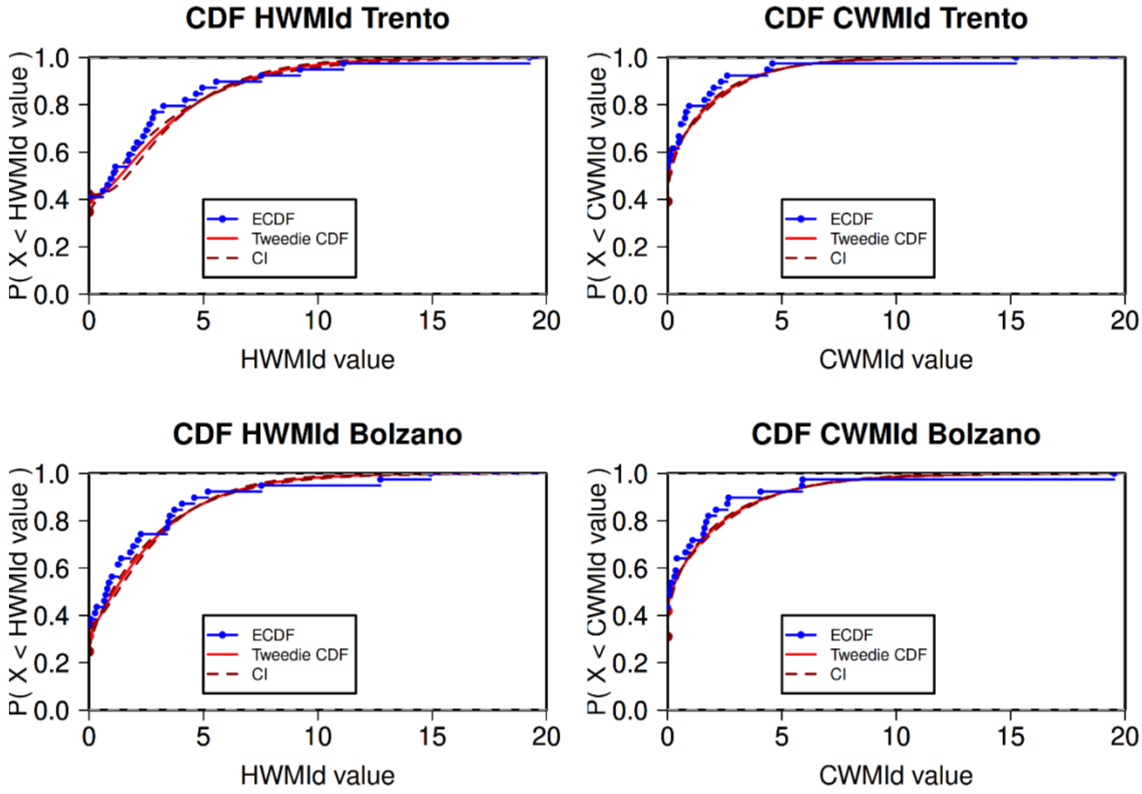


Figure S4: Cumulative distribution functions (CDF) for both HWMId / CWMId at the location of the cities of Bolzano and Trento, displaying the probability (P) showing the empirical cumulative distributions (ECDF) for these locations as well as the confidence interval (CI) of the power value of the Tweedie distribution.

3. Table 1: What are the exact definitions of “population living in at risk housing” and “population with low income”? Could you be more specific? And does the diploma/degree for “population with low education” refer to school or university degrees?

Thank you for the comment, we added more specific information in the table. Old table:

Table 1: Vulnerability indicators used (after Ho et al., 2018)

Category	Indicator	Definition
Extreme Age	Older Age	Population over 55 years old
	Infants	Population under 5 years old

Household physical characteristics	People in old houses	Number of household living in housing built prior to 1960
	People in poor living condition	Population living in at risk housing
Social Status	Low education population	Population with low education (no diploma or degree)
	People living alone	Number of single-person households
Economic Status	Low-income population	Population with low income
	Unemployed	Unemployment rate

New table:

Table 2: Vulnerability indicators used (after Ho et al., 2018)

Category	Indicator	Definition
Extreme Age	Older Age	Population over 55 years old
	Infants	Population under 5 years old
Household physical characteristics	People in old houses	Percentage of household living in housing built prior to 1960 (corresponding to when better insulation started being implemented)
	People in poor living condition	Percentage of household living in other type of housing not meant for inhabitation (cellar, attics)
Social Status	Low education population	Population with low education (no middle-school diploma)
	People living alone	Number of single-person households
Economic Status	Low-income population	Population in a household with children and no money-earning members
	Unemployed	Unemployment rate

4. Why has the year 1960 been used for the category “people in old houses”? Is this an arbitrary choice or are there reasons to choose this year?

   The year is not arbitrary, 1960 is first of all used in the study on which the indicators are based from (Ho et al, 2018). Second, the implementation of insulation dates from the 1960s, this has been specified in several studies about building insulations in several locations such as Austria or Italy (Mukati, 2021; De Angelis et al., 2020) and the first building energy regulation in Italy is from 1973 (Carrosio, 2015; Magnani et al., 2020), therefore it can be assumed that some building in an alpine region in Italy bordering Austria had insulations.

Carrosio, G.: Politiche e campi organizzativi della riqualificazione energetica degli edifici, Sociol. URBANA E RURALE, https://doi.org/10.3280/SUR2015-106002, 2015.

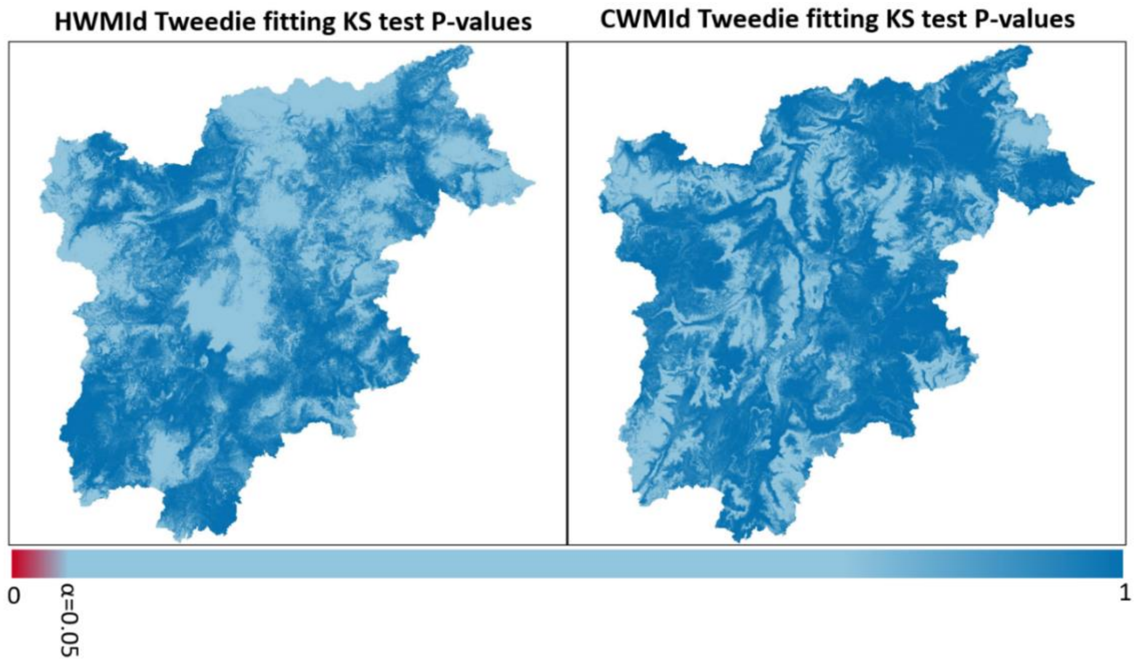
De Angelis, A., Ascione, F., De Masi, R. F., Pecce, M. R., and Vanoli, G. P.: A Novel Contribution for Resilient Buildings. Theoretical Fragility Curves: Interaction between Energy and Structural Behavior for Reinforced Concrete Buildings, Buildings, 10, 194, https://doi.org/10.3390/buildings10110194, 2020.

Magnani, N., Carrosio, G., and Osti, G.: Energy retrofitting of urban buildings: A socio-spatial analysis of three mid-sized Italian cities, Energy Policy, 139, 111341, https://doi.org/10.1016/j.enpol.2020.111341, 2020.

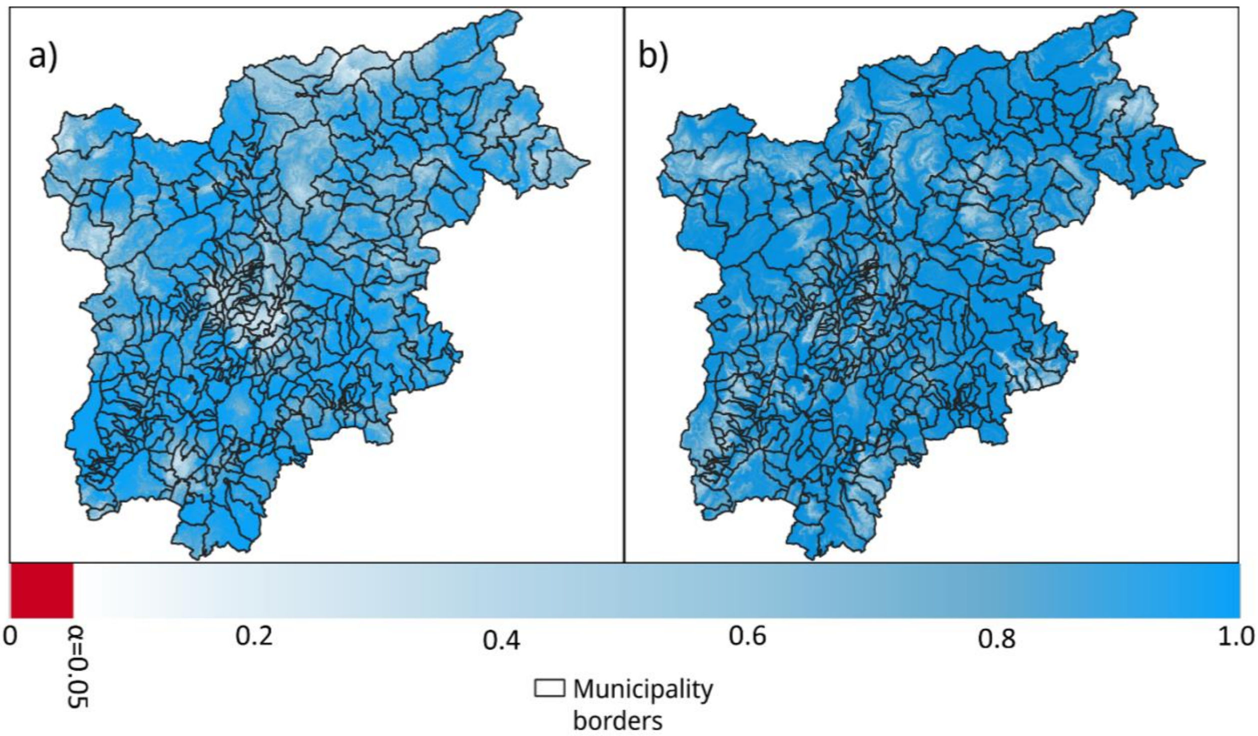
Mukati, A.: Effect of Heatwaves on the Cooling Demand of Austrian Residential Buildings, 2021.

5. Figure S-3: I wonder whether it would make sense to add the borders of the municipalities/districts shown in Figure 4 also to this figure. Moreover, I would suggest to use a linear color scale between 0.05 and 1 and add more ticks to the colormap (not just 0, 0.05, and 1)

The figure was remade to account for the reviewer comment. The old figure was:



the new revised figure is.



6. Figure 4: I think it would be good to add a figure (or a subplot) that shows the evolution for the four cities as it is impossible to identify them and to see their changes just from the maps. Also, what do the black borders in the figures depict? Is it municipalities or districts? This should be added in the caption.

We thank the reviewer for the comment we created a new figure and placed in the supplementary material according to the suggestion. The new added figure is:

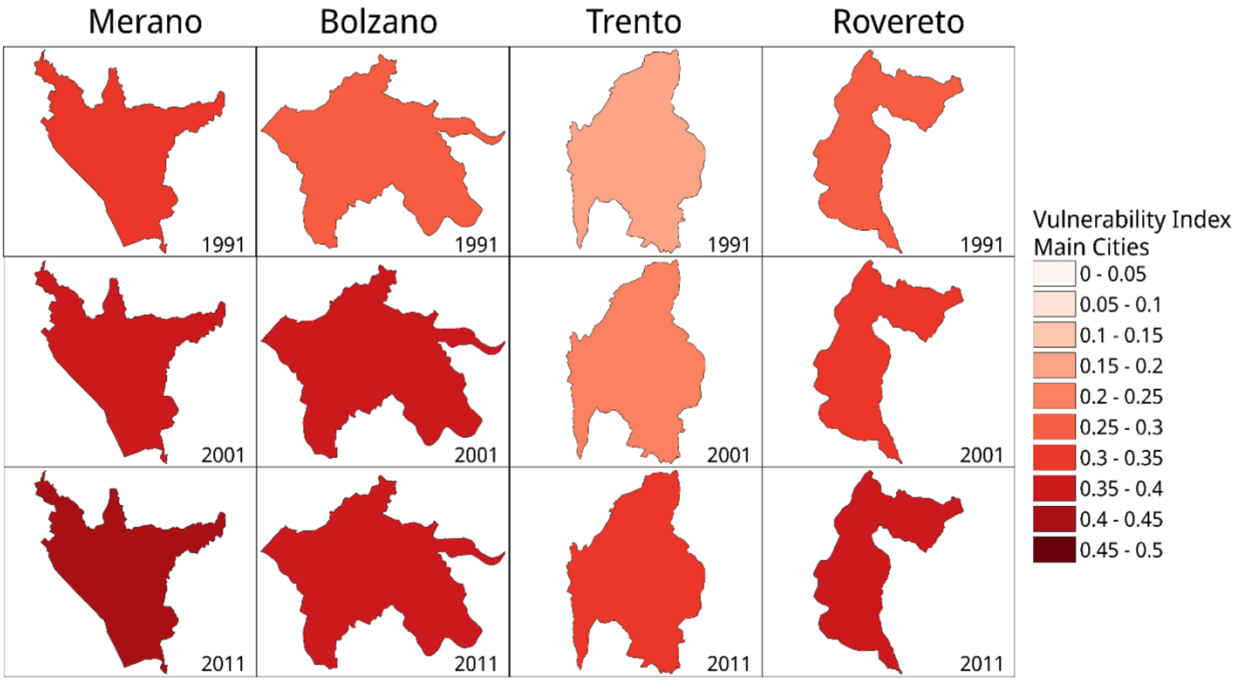


Figure S5: Evolution of the vulnerabilities of the 4 large cities of the region (Merano, Bolzano, Trento and Rovereto).

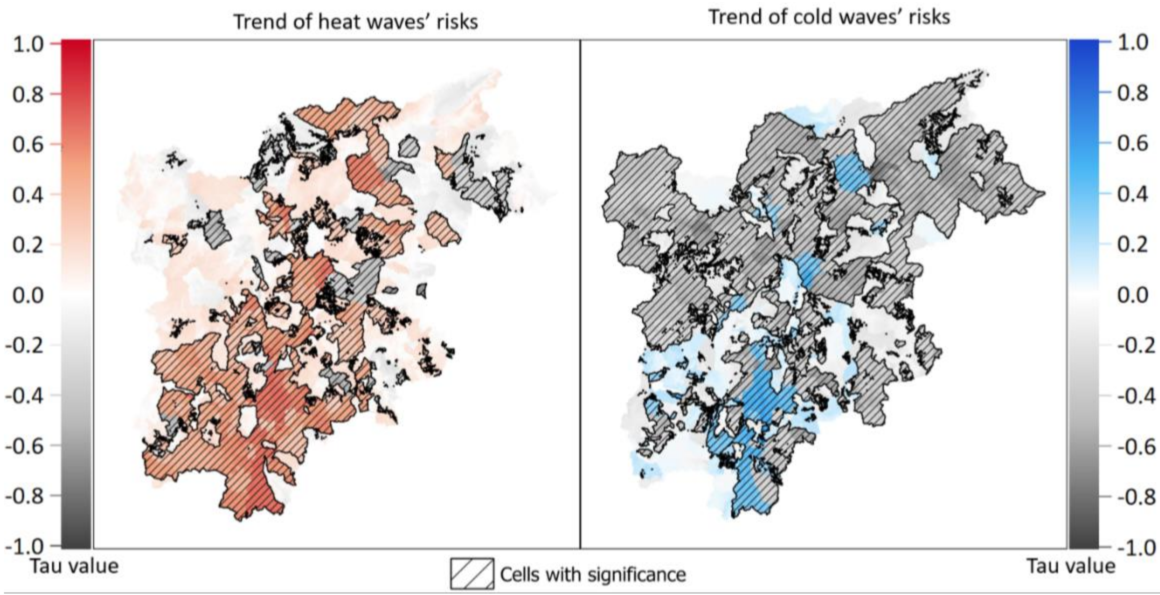
Moreover, the black borders are municipality, and this was added in the caption of the revised figure. The old caption was Figure 3: Calculated vulnerability index for the three years of the census records (1991, 2001, 2011)

The new caption is:

Figure 4: Calculated extreme temperatures vulnerability index for the three years of the census records (1991, 2001, 2011) with the borders of the municipalities in black.

7. Figure 5: The trends are difficult to see due to the many hatching lines. I would suggest having only fewer hatching lines (like in Figure 2). Also, how is it possible to see that a trend is positive or negative? (the tau values are positive both for HWs and CWs). Like for Figure 4, I'd suggest adding a separate panel showing the results for the four cities.

The Figure was remade, the cities were added directly on it and are visible. The old figure was:



The new figure is: